UCRL-PRES-233997

Laboratory Experiments, Numerical Simulations, and Astronomical Observations of Supersonic Jets in Clumpy Environments

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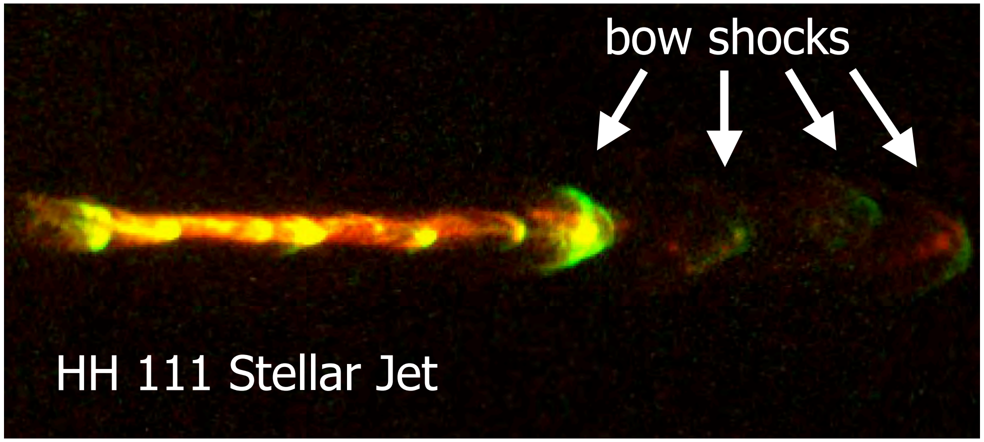
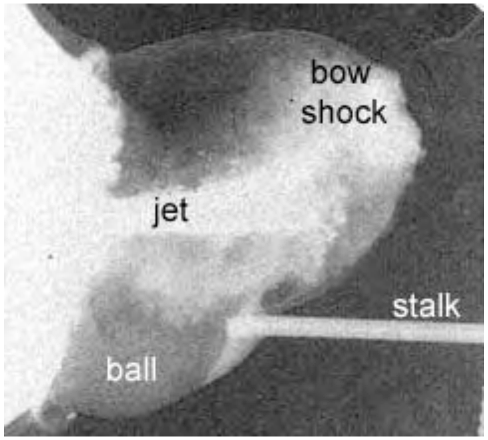
Numerical Simulations: Bernard Wilde and Robert Coker (Los Alamos), Paula Rosen (AWE), Adam Frank (Rochester), Robert Carver (Rice), Jacob Palmer (Rice)

Laboratory Experiments: John Foster (AWE), Freddy Hansen (LLNL), Brent Blue (GA), Robin Williams (AWE)





Work performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.
UCRL-PRES-233997

Motivation

- To gain a better understanding of stellar jets by combining:
  - Laboratory Experiments
  - Numerical Simulations
  - Astronomical Observations
- Code Validation and Extension (AstroBEAR, RAGE and PETRA)
- A truly multidisciplinary project (Los Alamos numerical modelers travel to telescopes to observe; astronomers present at Omega laser shots)
- Involve Ph.D. thesis students in NNSA-related research

Project Outline

- Experimental
  - Develop OMEGA Laser shots that are analogs to shock waves in stellar jets
- Numerical
  - RAGE and PETRA to support target design, and AstroBEAR to model astronomical observations
  - Extend the codes so they can work on each other's problems
- Astronomical
  - Multi-epoch emission line images from HST to follow proper motions and make movies to compare with simulations
  - Ground-based radial velocity maps of extended sources to measure internal motion `datacubes' and develop methods for comparing these to simulations

Talk Outline

- I. Overview of Stellar Jets
  (a) Radiative Shocks (Astronomical Definition)
  (b) Observational Parameters

- II. Omega Laser Shots
  (a) Scaling
  (b) Target Design
  (c) Results from Shots

- III. Numerical Simulations
  (a) Extend RAGE to work on astrophysical problems
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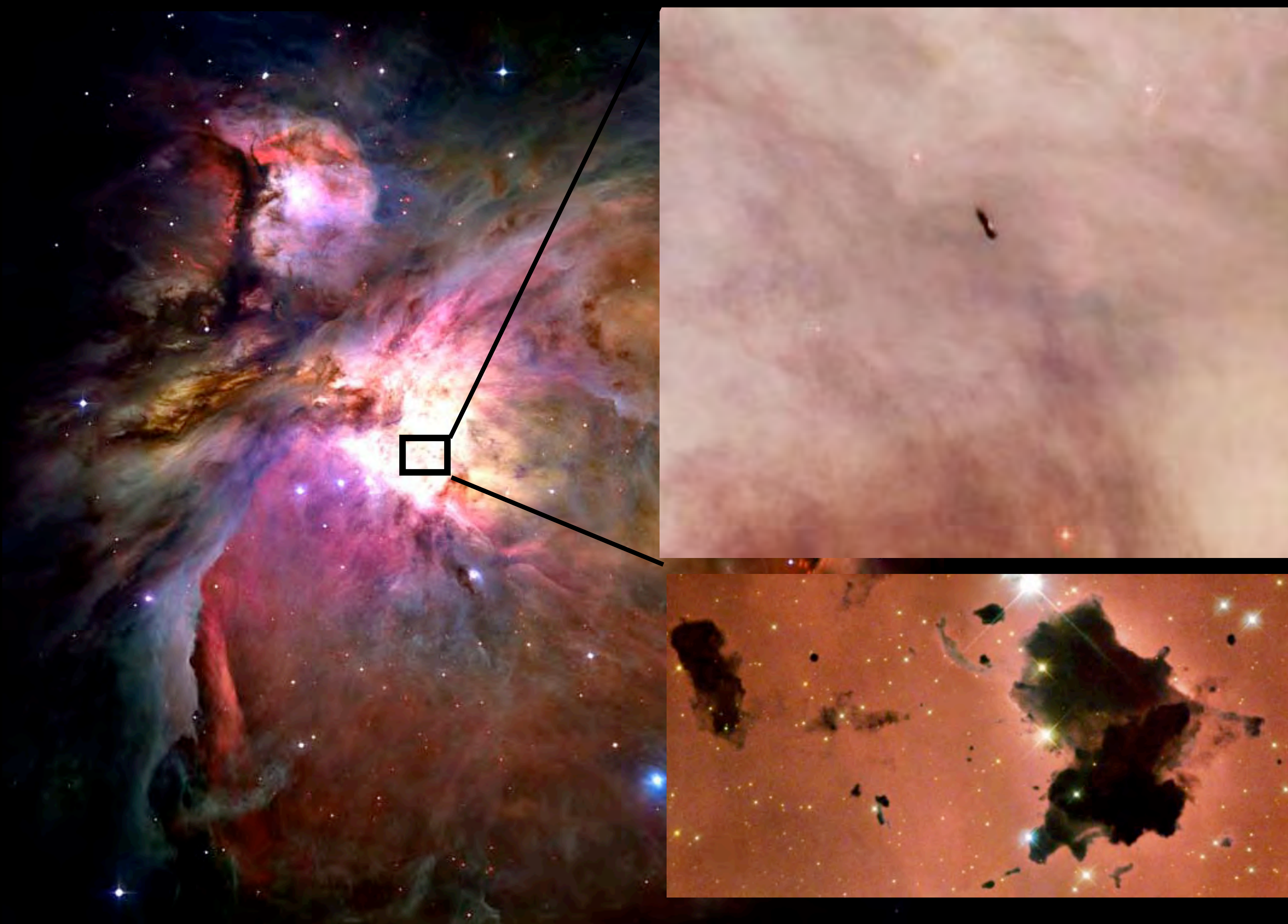
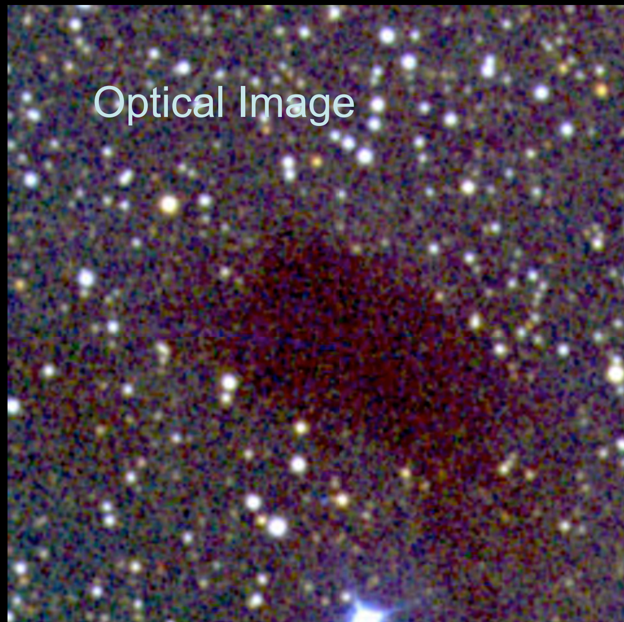
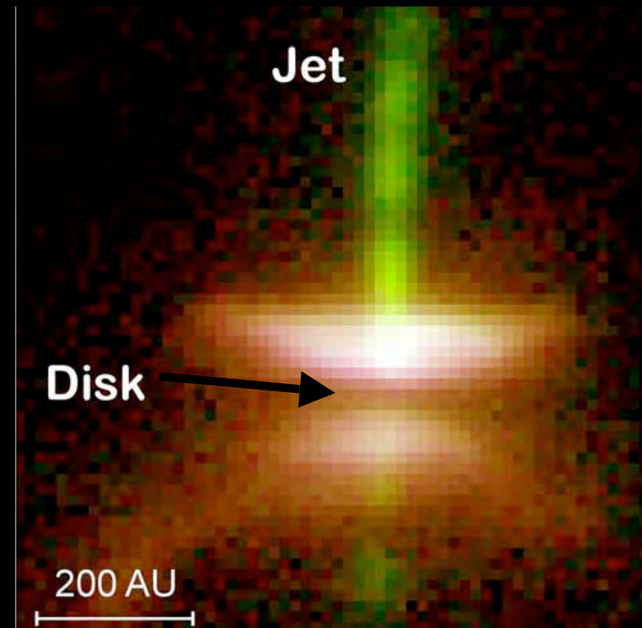
- IV. Astronomical Observations
  (a) Current HST project
  (b) Slit-mapping radial velocities from Kitt-Peak

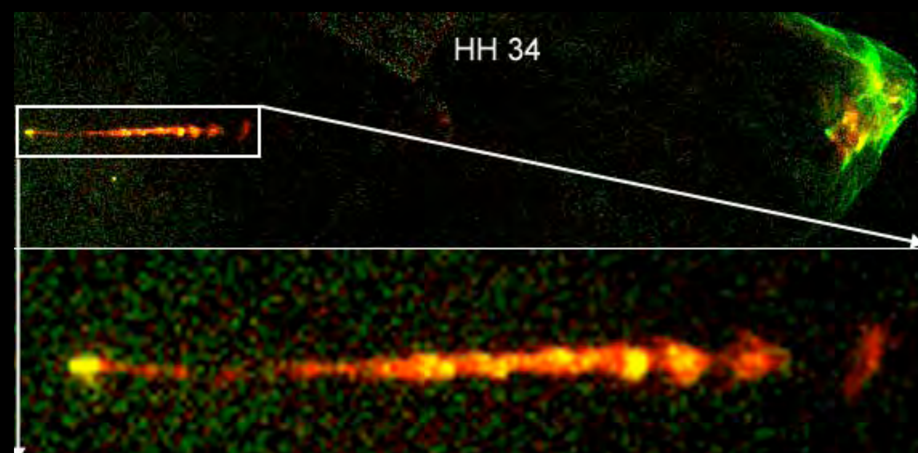
Overview of Stellar Jets





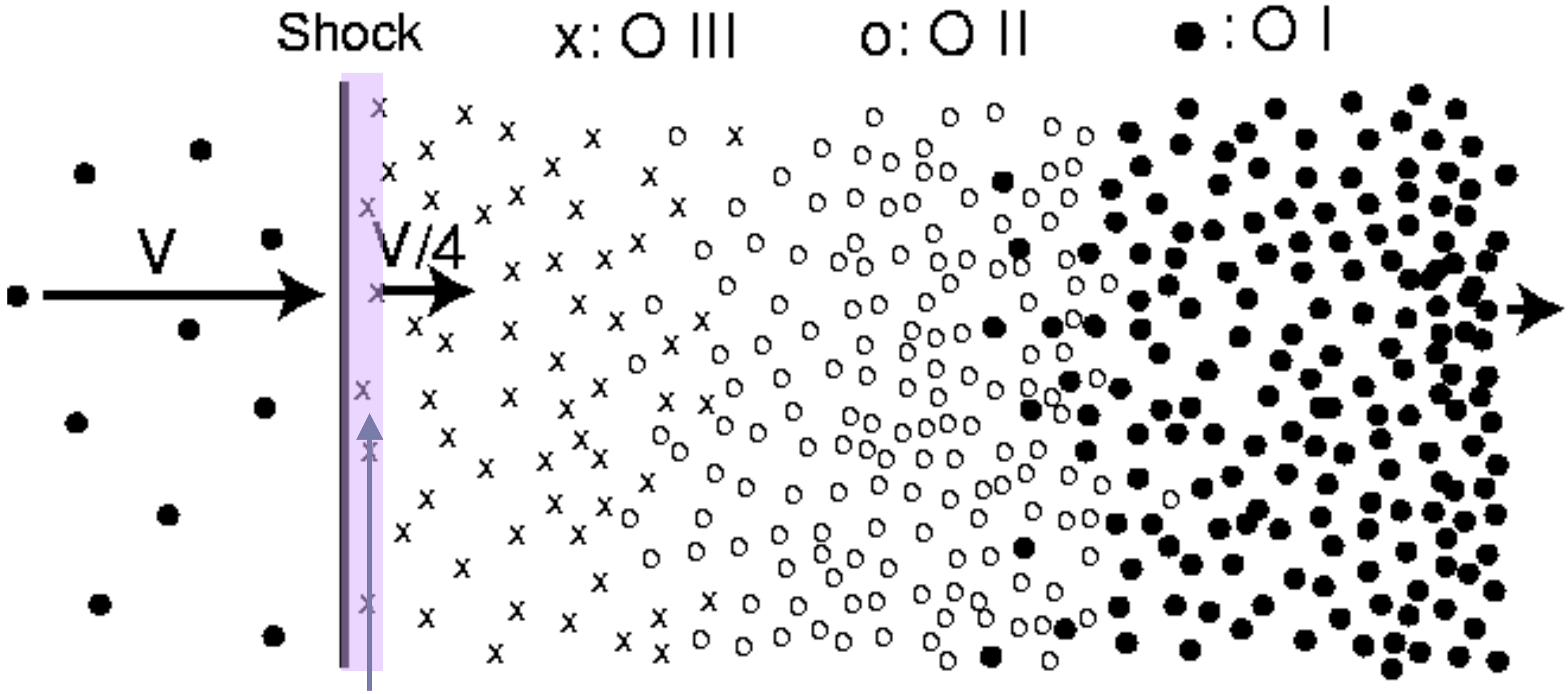


Burrows et al 1996



Reipurth et al 2001

Radiative Shock: One that cools by emitting photons that escape

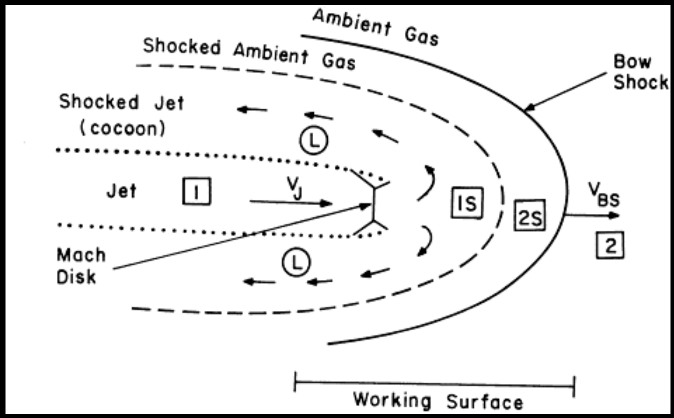


Layer of Collisionally-excited H @ shock

Entire Cooling Zone is optically thin to optical and IR photons

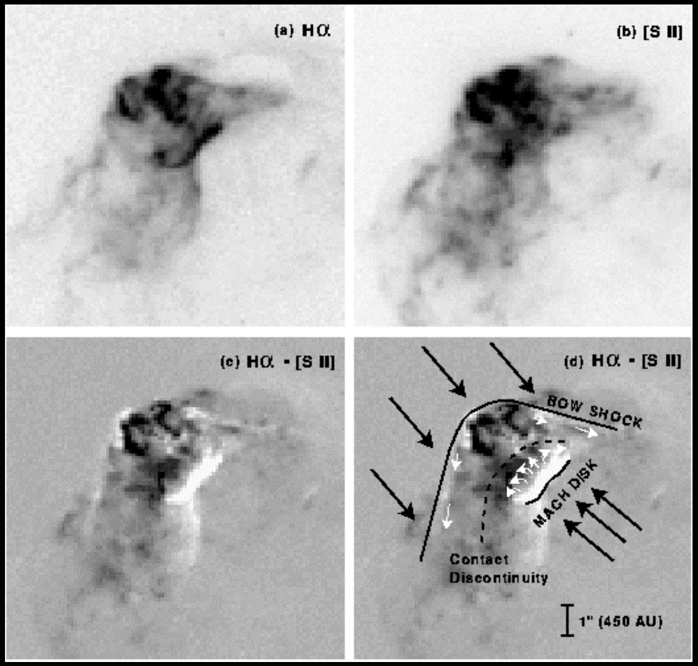
Emission Lines give Doppler velocities, line ratios give temperature and density

Bow Shock/Mach Disk Structures

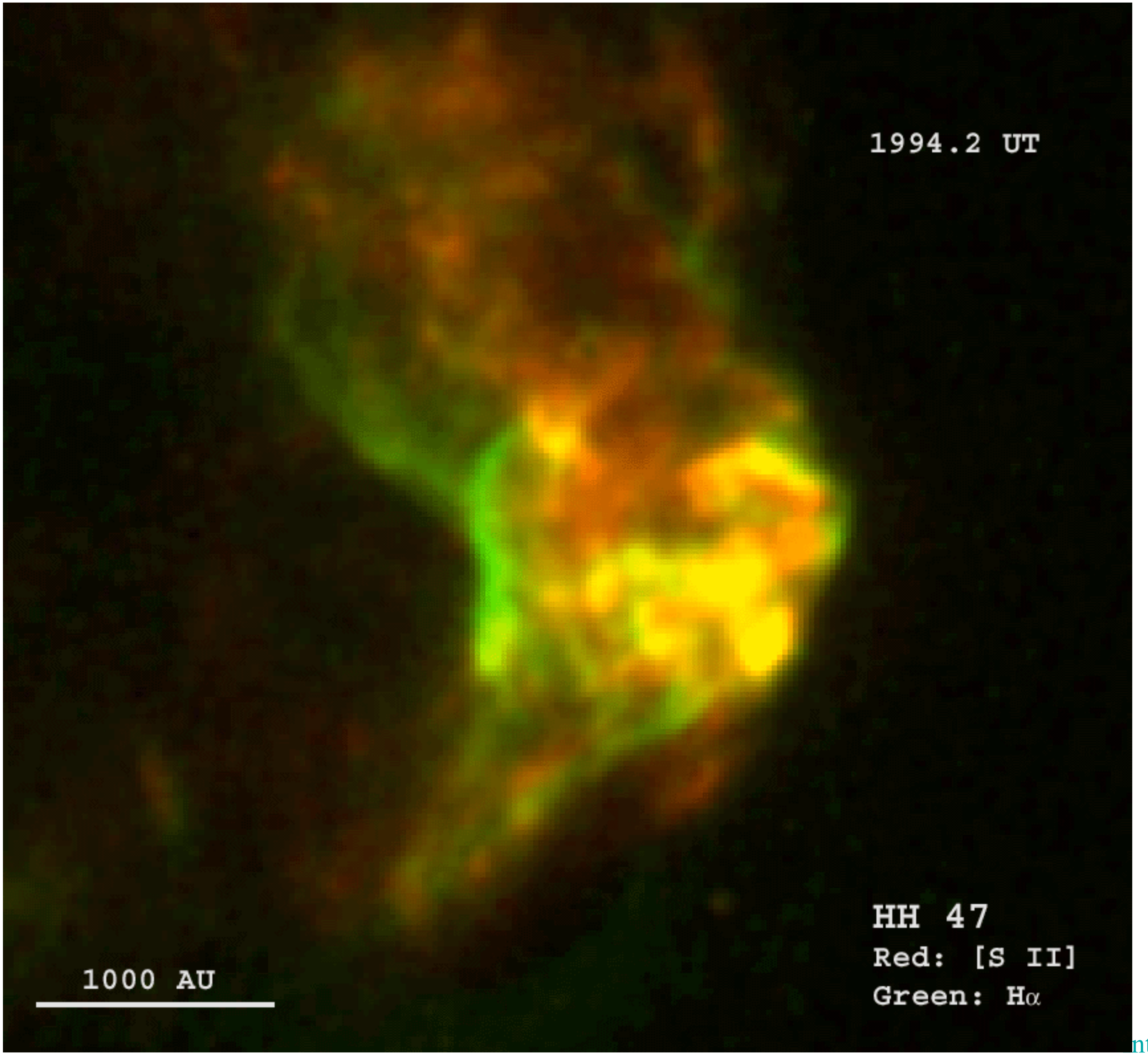


Hartigan 1989 ApJ 339, 987

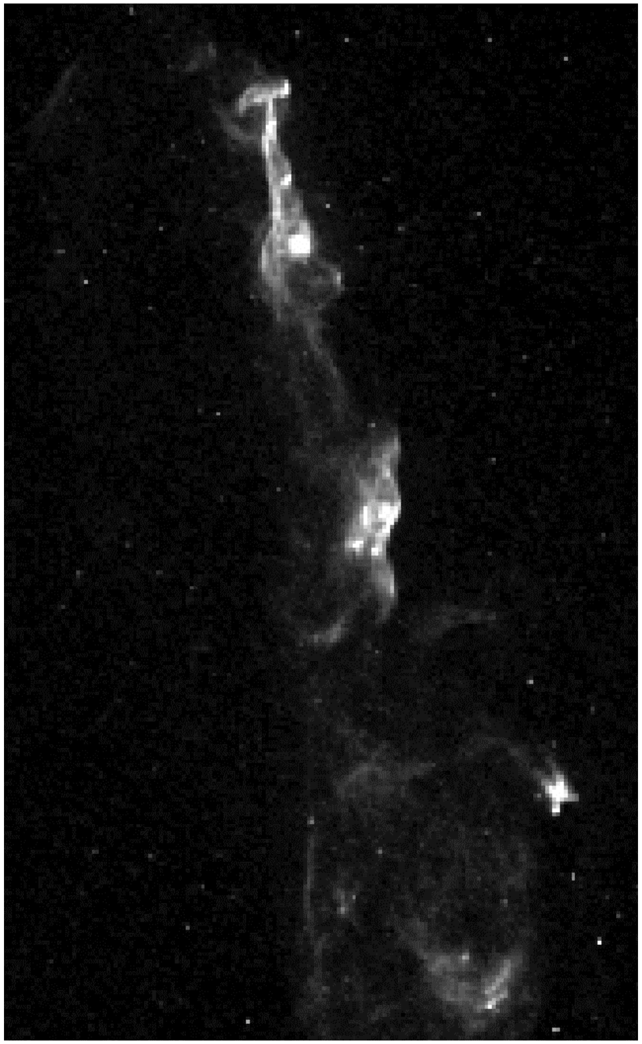
Reipurth & Heathcote1992 A&A 257, 693



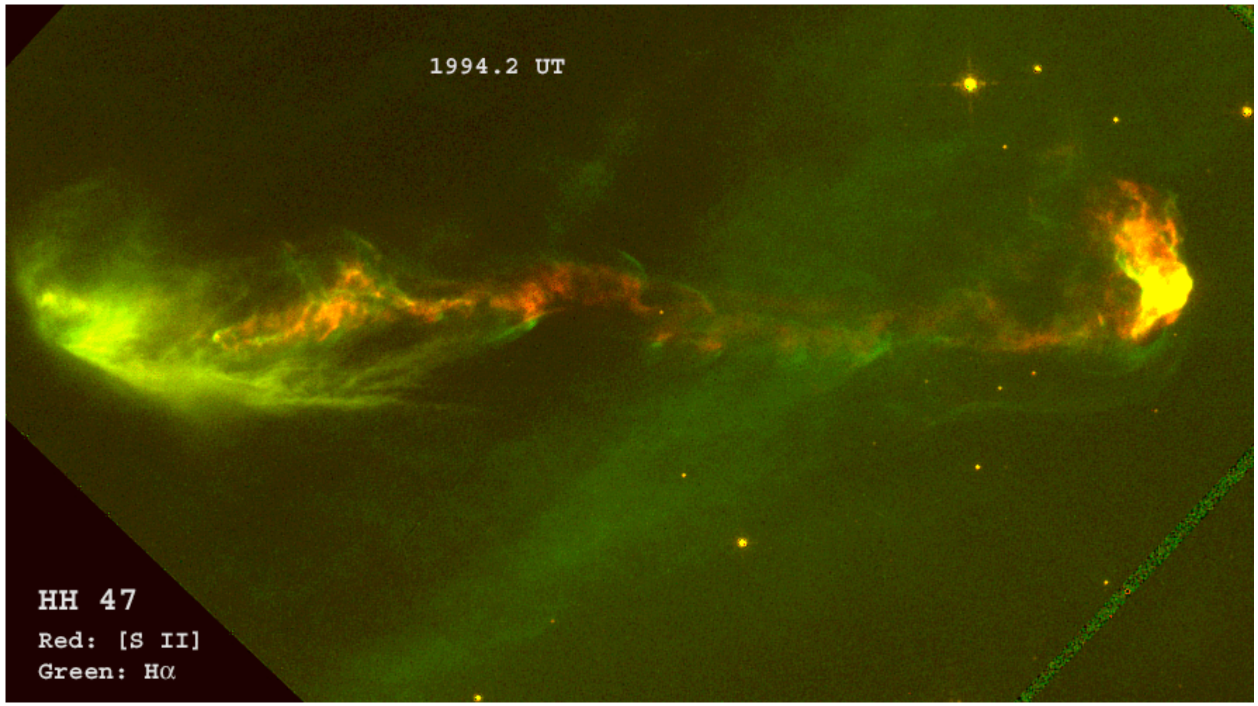
Heathcote etal 1996


1994.2 UT
HH 47
Red: [S II]
Green: Hα
1000 AU

HH 110



HH 47



Typical Jet Parameters

Velocity: 100-500 km/s
Width: Typically 100 AU (1.5×10^{10} km) @ d=1000 AU
Length: Can extend out to 1 pc (10^{13} km)
Opening Angle: 2-20 degrees
Density: 10^4 cm^{-3} (10^{-20} g cm^{-3})
Composition: Cosmic, i.e. mostly H
Ionization Fraction: 2% - 20%
Differential Knot Velocity: 30-50 km/s
Magnetic Field: Poorly known. < 1mG at large distances
stronger closer to source

Main point: Multiple, nested bow shocks from velocity
variability. Internal shocks heat jet. Jets are clumpy

Observations: Emission line radiation gives density,
temperature, radial velocity. Proper
motions visible over several year timespan

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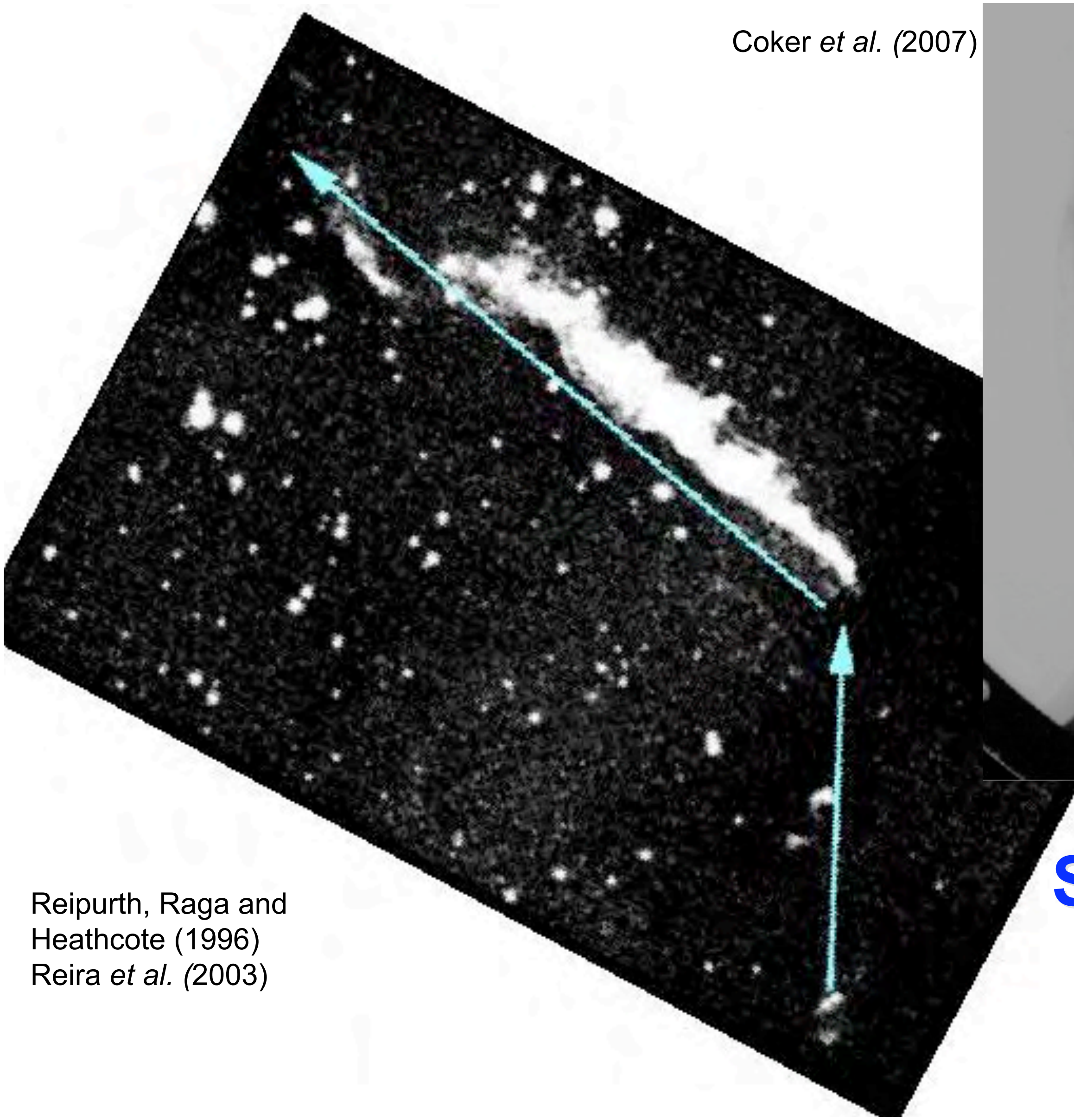
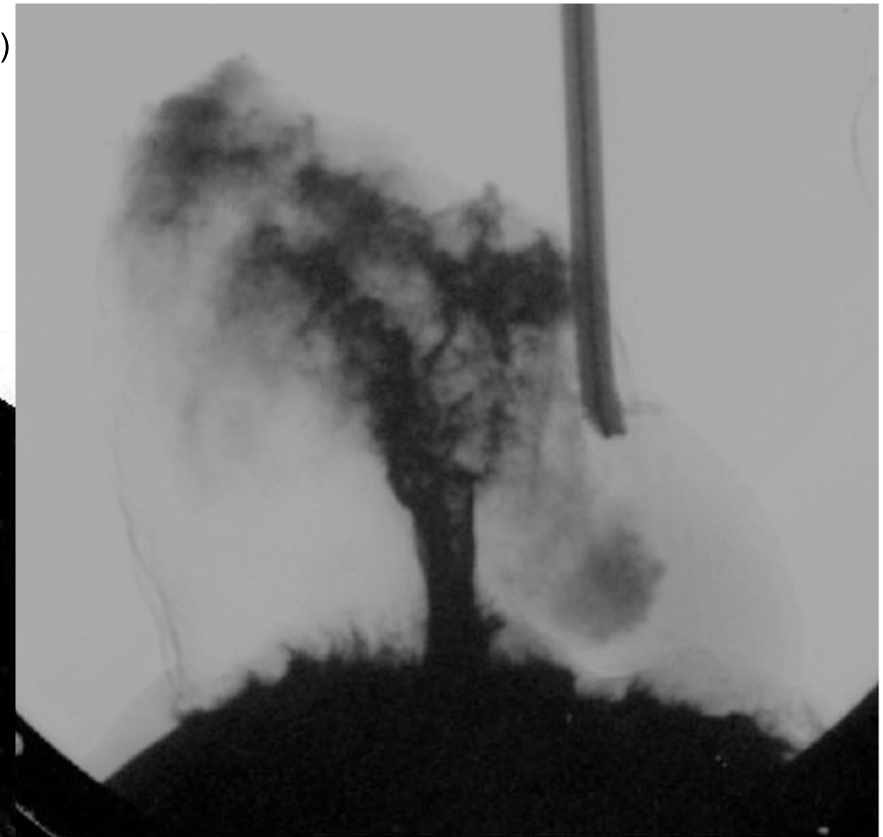


Reipurth, Raga and
Heathcote (1996)
Reira *et al.* (2003)



Coker *et al.* (2007)

Scaling from mm to 10^{13} m

What can we learn about an object such as HH 110 (left) using laboratory experiments such as those on Omega (right)?

Astrophysical Scaling

- Some questions require controllable and repeatable 3D experiments and simulations to answer
- If ‘similar enough’, then an experiment will behave in the ‘same way’ as an astrophysical object
- Need to *define* similarity and find what *aspects* of the two systems will behave in the same fashion
- Example: self-similarity, where the solution to a problem does not depend *explicitly* on all variables but on a *combination* of them (Sedov, conduction)

Dimensionless Numbers

Ryutov, D. et al. 2000

- Two systems with the same Euler (~Mach) number (and scaled initial conditions and boundary conditions) will behave identically

$$Eu \equiv \mathrm{v}\sqrt{\rho / p}$$

- Experiments are Euler-scaled but not cooling-scaled

- Easier to scale from experiment to astrophysical object than the other way around

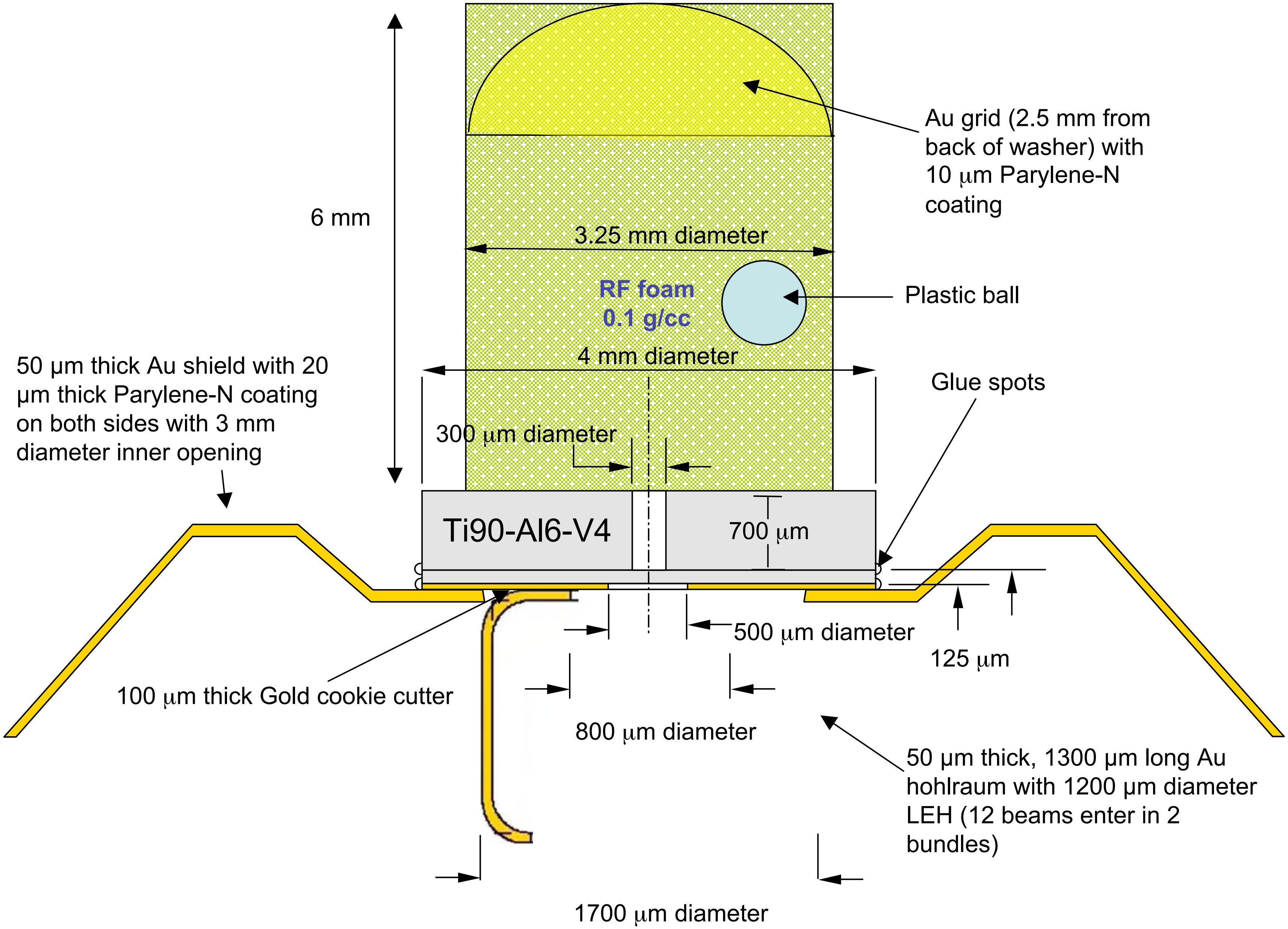
Scaling Example: YSO jet

- Mach 30; $P \sim 10^{-9}$ dyne/cm^2; $\rho \sim 1\times10^{-21}$ g/cc

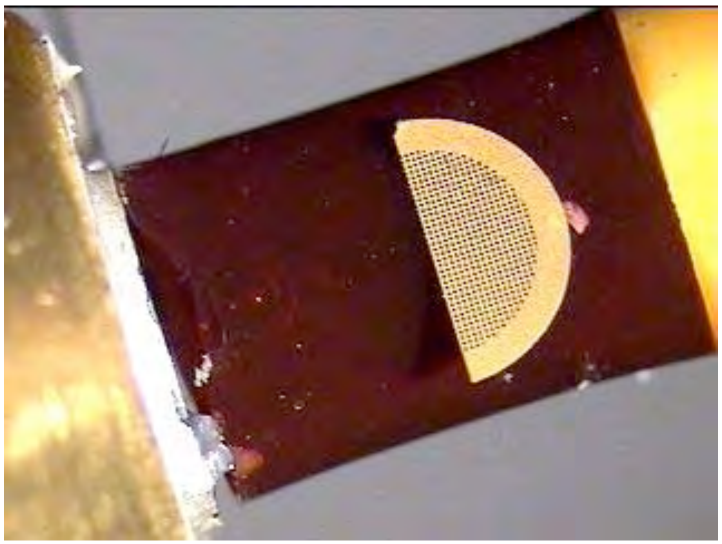
- Omega laser limit $\sim 10^{11}$ dyne/cm^2
- Constant *Eu* → choice of v or ρ (usually the latter is more controllable but with less dynamic range)
- Pick $\rho \sim 1$ g/cc → $v \sim Eu\sqrt{(P/\rho)} \sim 100$ km/s

- Temporal and spatial scales also limited by Omega laser facility
- Pick ~100 μm → $t \sim L\sqrt{(\rho/P)}) \sim 50$ ns to model the jet evolution for ~100 years

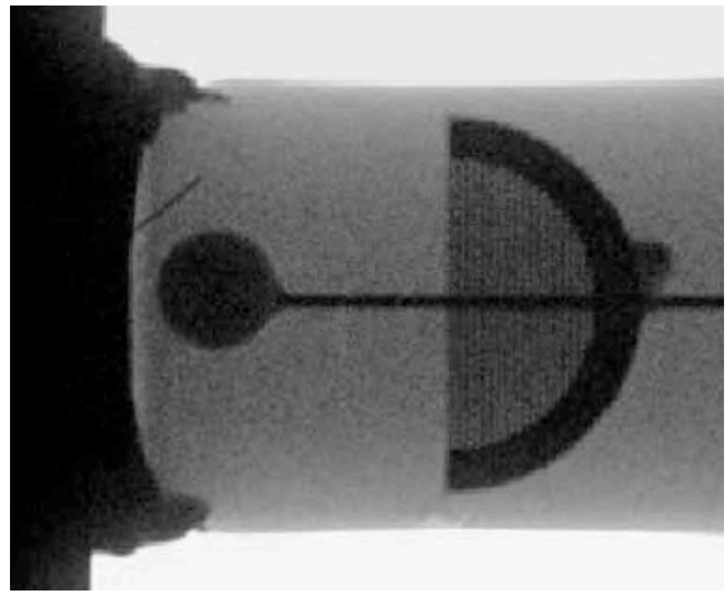
Omega Laser Targets



Target Metrology

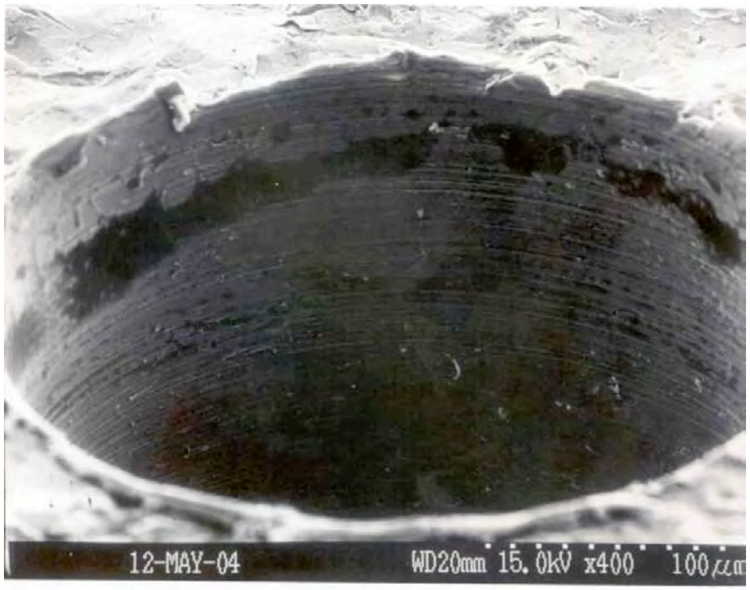


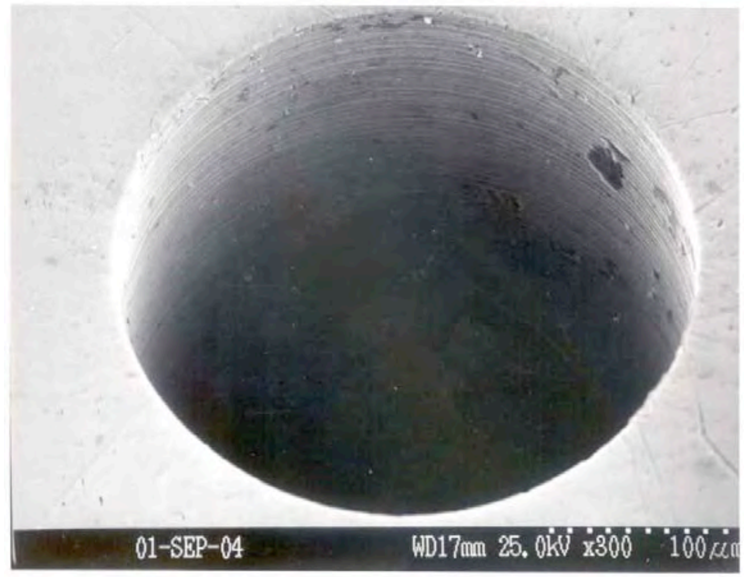
Optical



X-Ray

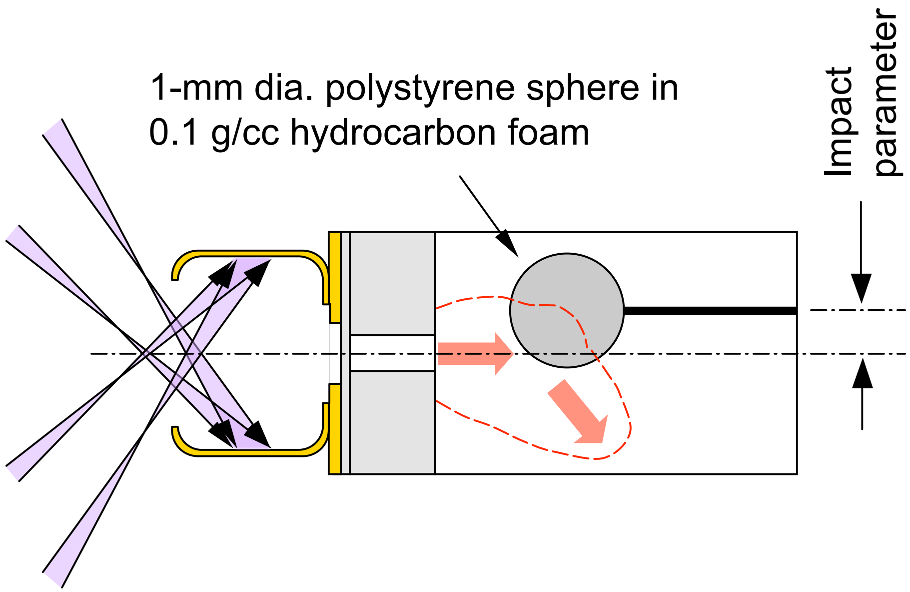
Targets require precise manufacturing

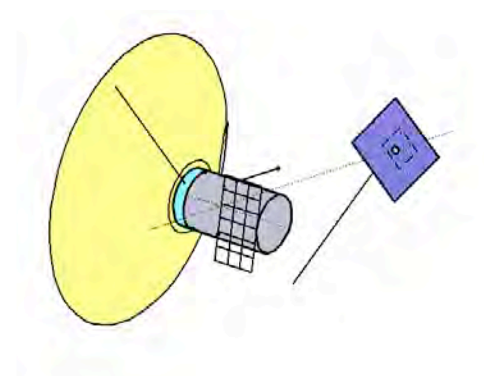




e.g. Don’t want details of shape of hole to dominate results

Experimental Design

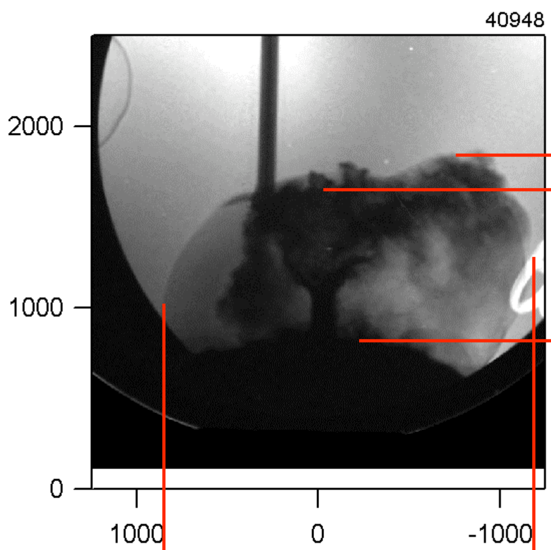


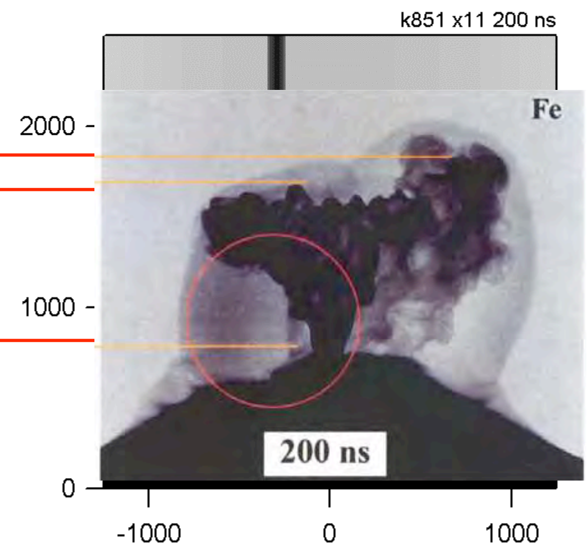


- 12 beams ablate the gold hohlraum walls producing a pressure pulse towards the target to the right
- Plug of material flies down empty region, breaks out into the foam, and is imaged in X-ray
- Point-projection X-ray backlighters and fast, gated framing cameras image the experiment

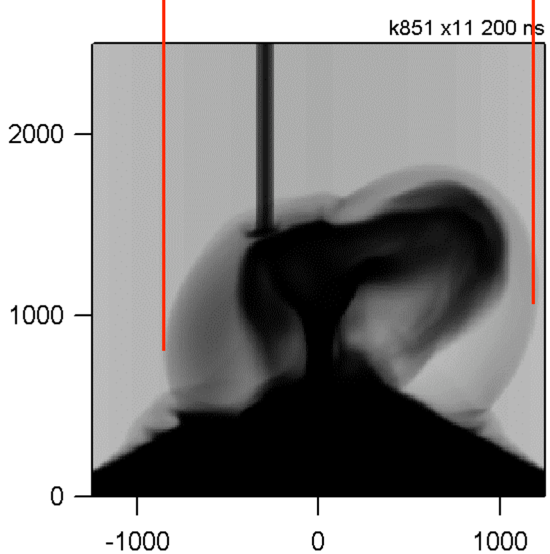
Data & Simulation Images

300 μm impact parameter, 6.7 keV backlight, *t* = 200 ns



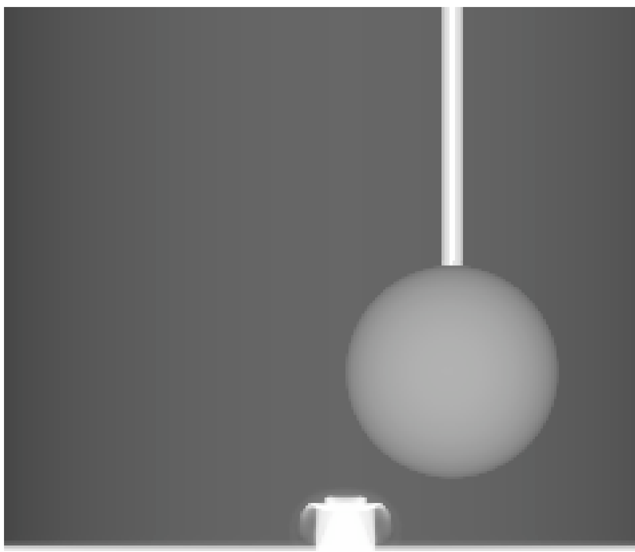


High resolution required to get ‘mixing’ right (as expected due to low *Re*)

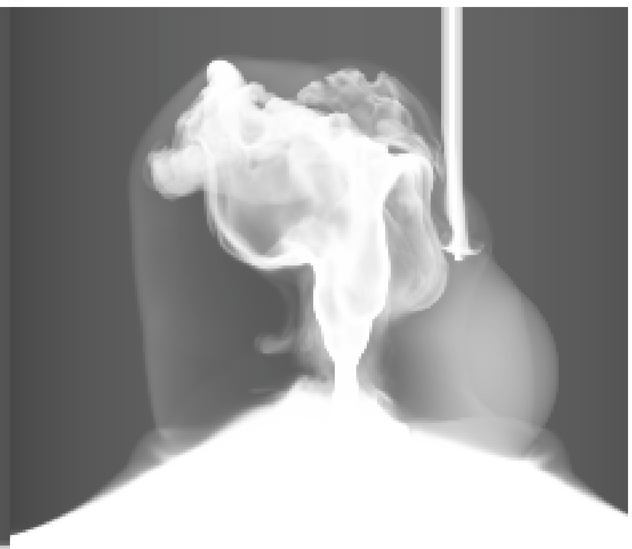


But even low resolution simulations get much of the large-scale structure right. Lack of knowledge of initial conditions and the laser drive prevent small-scale structure modelling.

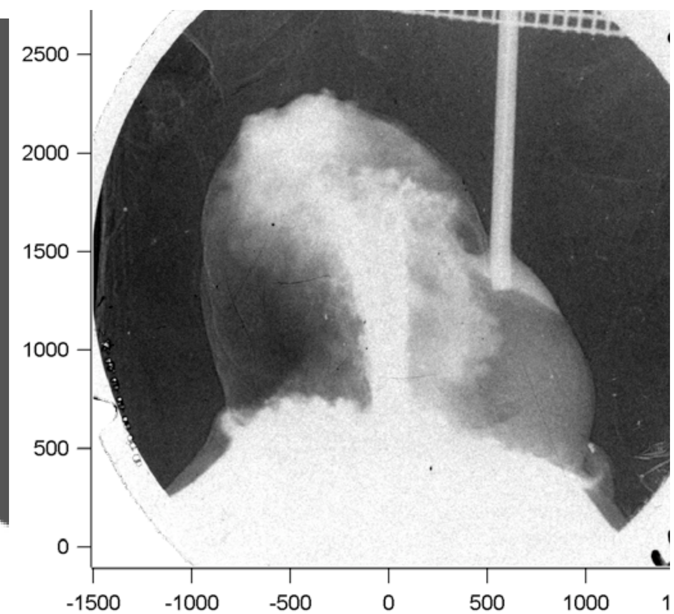
3D RAGE simulation (3 μm resolution) of jet deflection by 1000 μm diameter ball embedded in foam with impact parameter of 500 μm.



Fe backlighter
from 40 to 200 ns
at 0 degrees



Fe backlighter
at 200 ns every 10 degrees



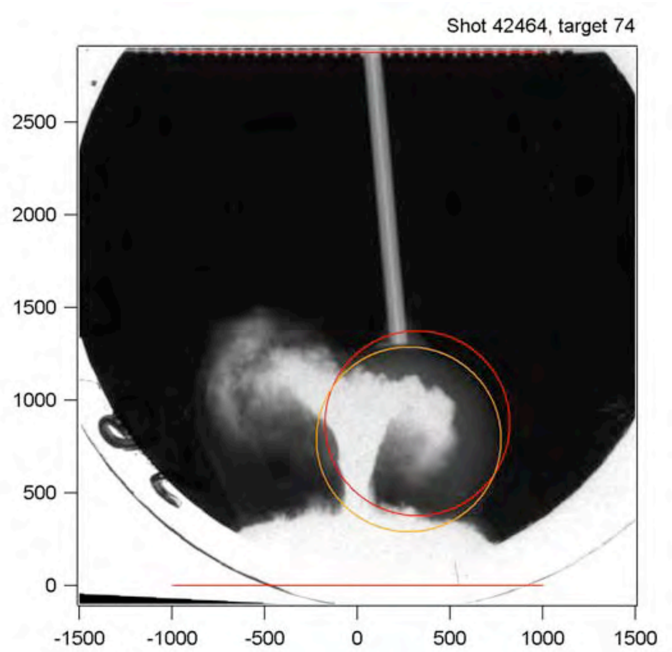
Fe backlighter
Data at 200 ns

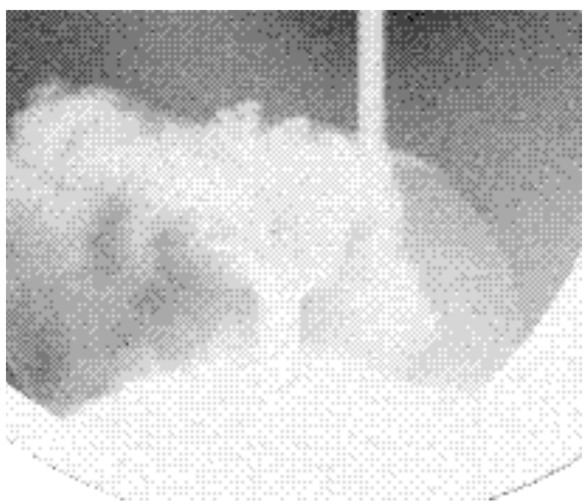
Experimental Results
(Jet deflecting from obstacle)

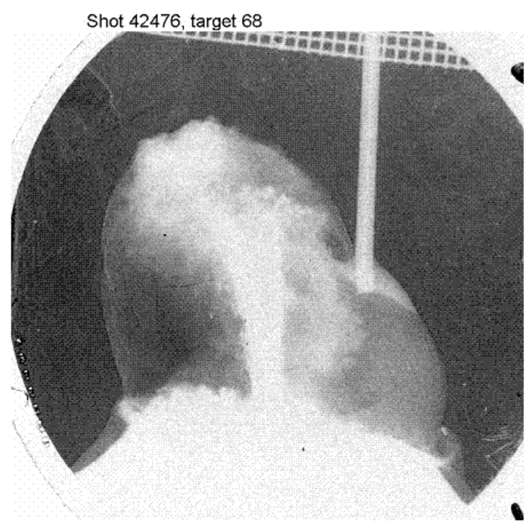
250 microns @
200 ns

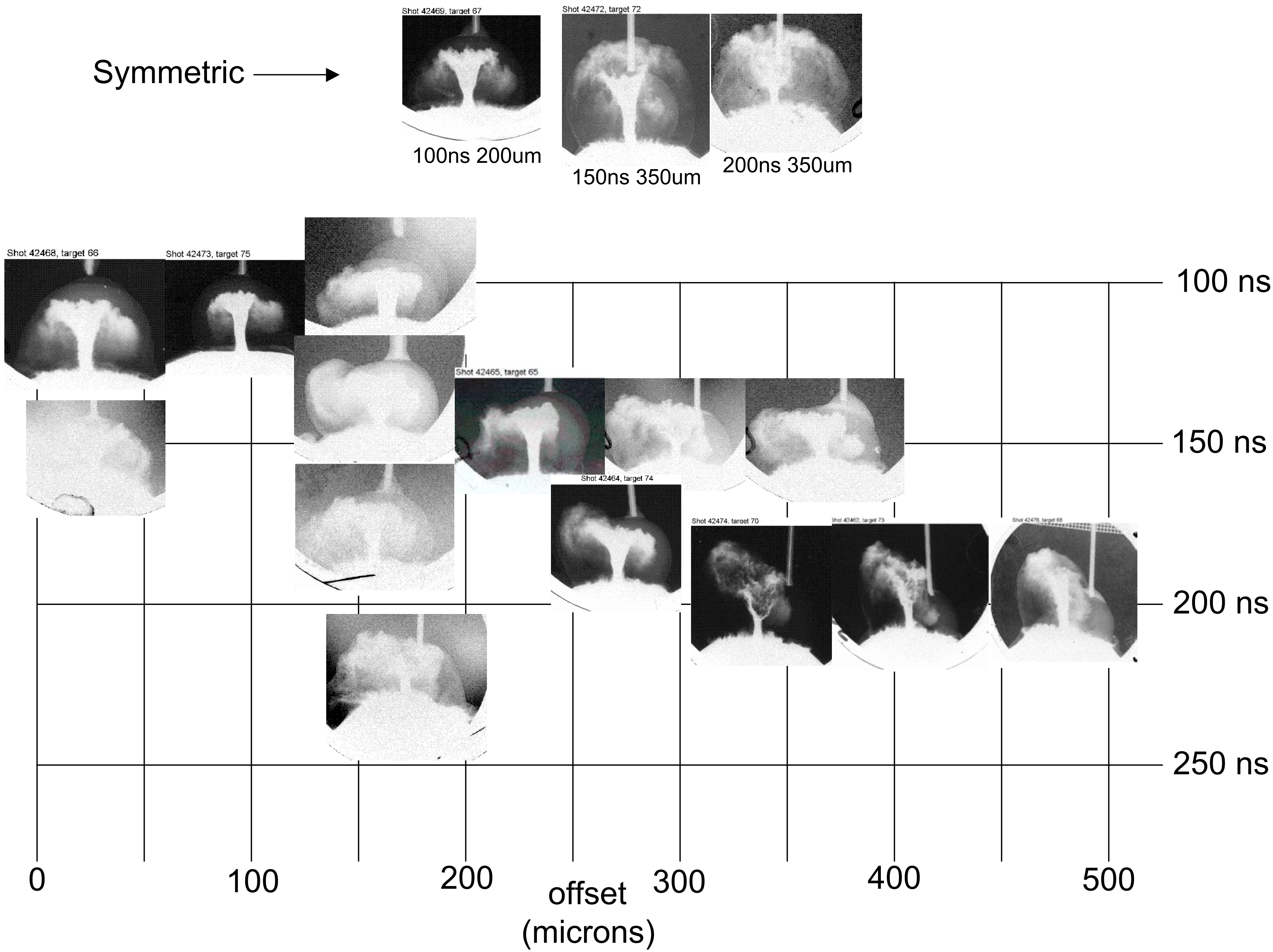
350 microns @
150 ns

500 microns @
200 ns







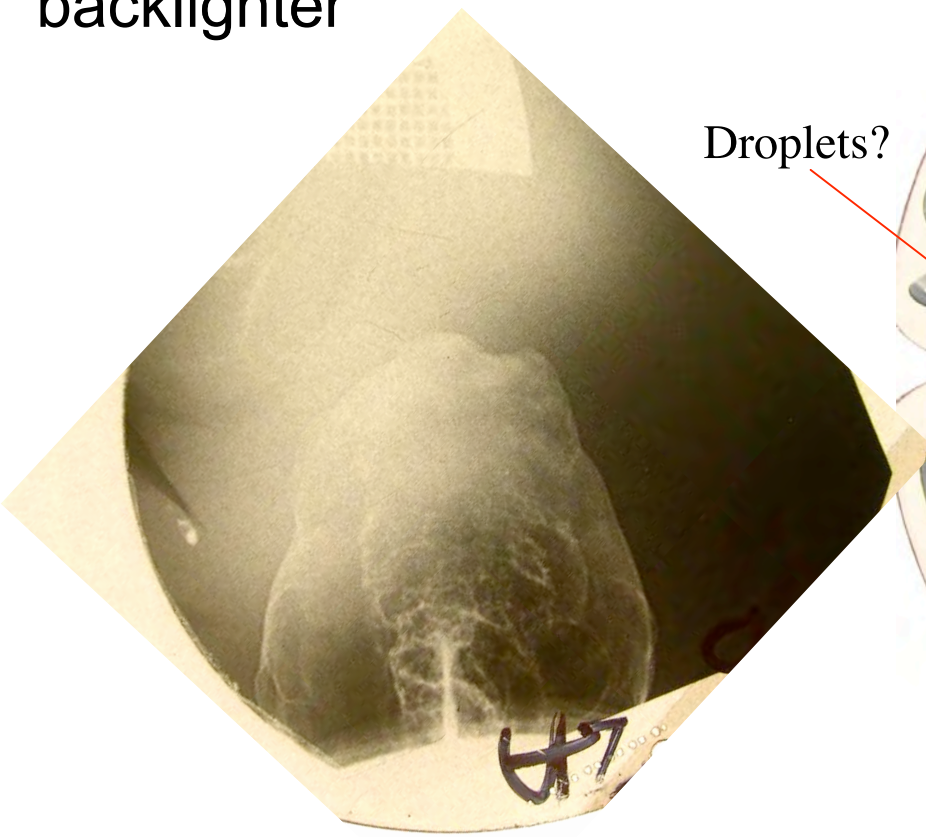


Symmetric
Shot 42469, target 67
100ns 200um
Shot 42472, target 72
150ns 350um
200ns 350um
Shot 42468, target 66
Shot 42473, target 75
Shot 42465, target 65
Shot 42464, target 74
Shot 42474, target 70
100 ns
150 ns
200 ns
250 ns
0
100
200
300
400
500
offset
(microns)

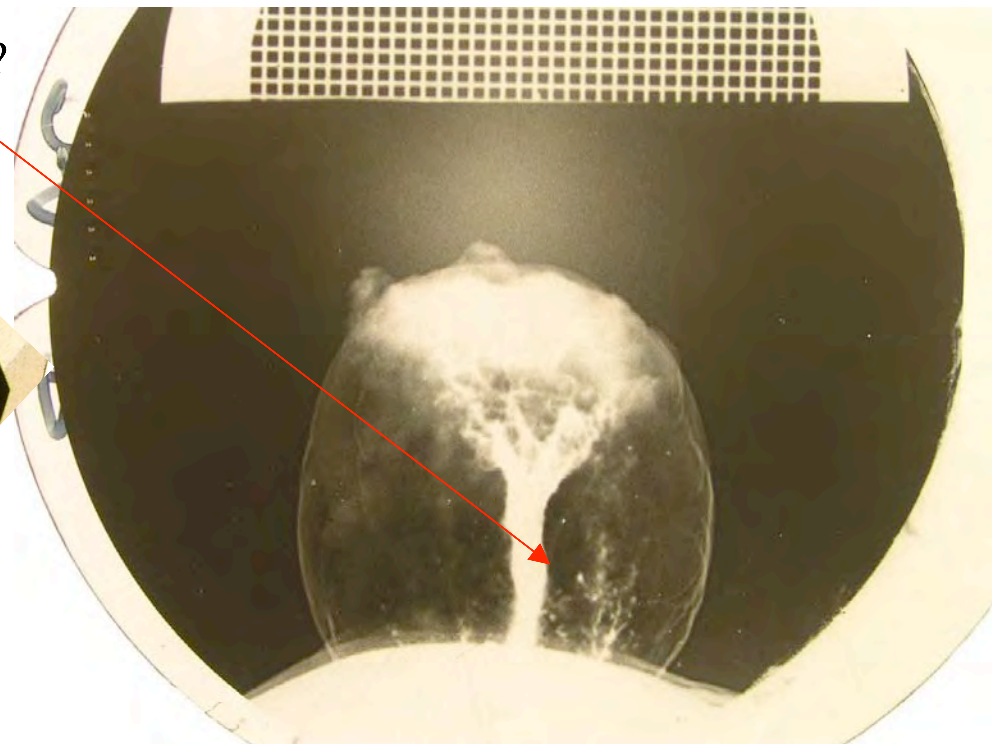
Blue

Different backlighter X-ray energies

Jet after 200 ns of evolution asseen with both a Ti and V backlighter



Ti backlighter



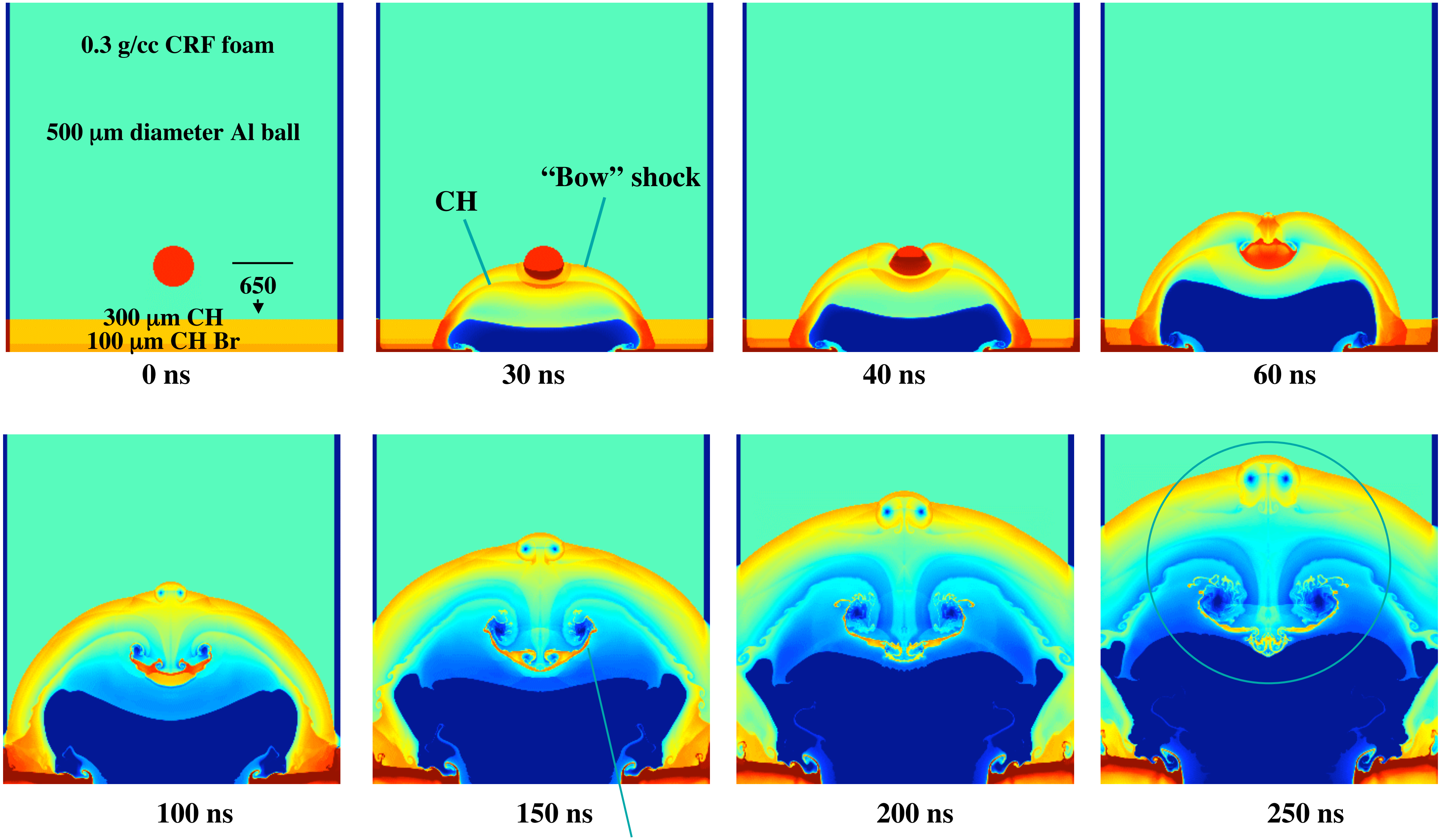
V backlighter

BL Drive: 2803 J

T = 200 ns

BL Drive 2171 J

Next set of experiments Widnall unstable



Should go 3D: width ~30 μm (~20 resolution elements)

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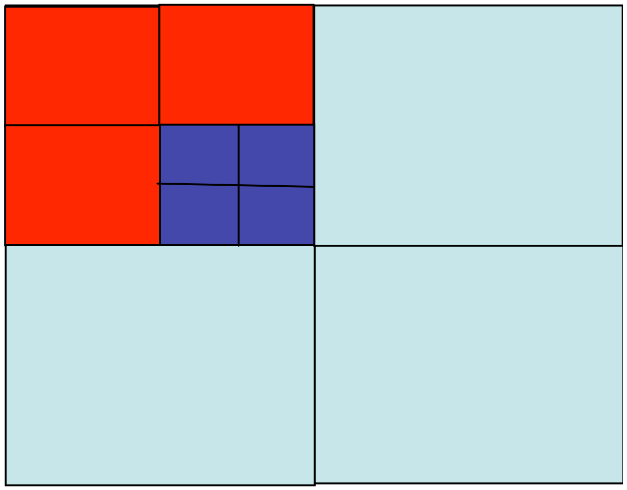
The Omega Experiments are part of a large V&V Program

- Aid in benchmarking various radiation hydrodynamic codes:
  - LANL: LASNEX, RAGE
  - AWE: NYM, PETRA, TURMOIL, HYDRA
  - U. of Chicago: ALLA, FLASH
- Example: Radiation Adaptive Grid Eulerian
  - Godunov hydro (no artificial viscosity, just numerical…)
  - Implicit 2T radiation diffusion
  - CAMR

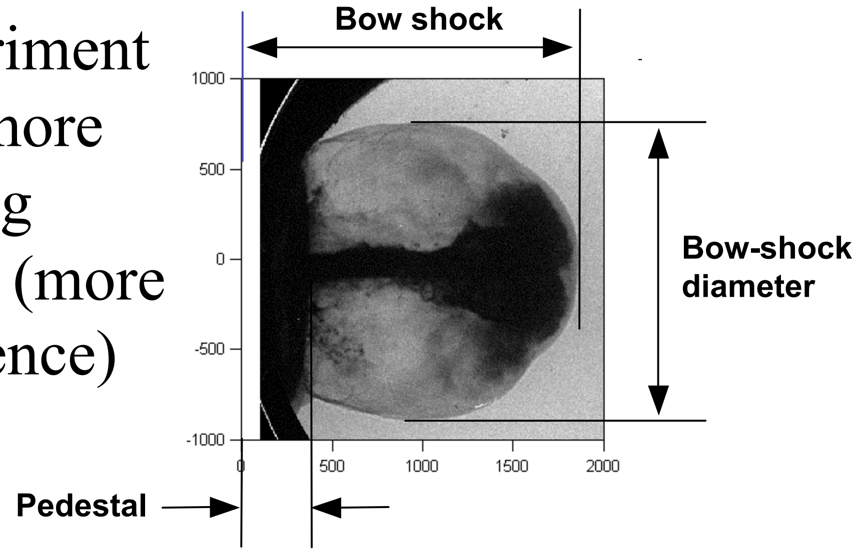
  Experiments illustrated a bug concerning shocks that converge at r=0 in RZ



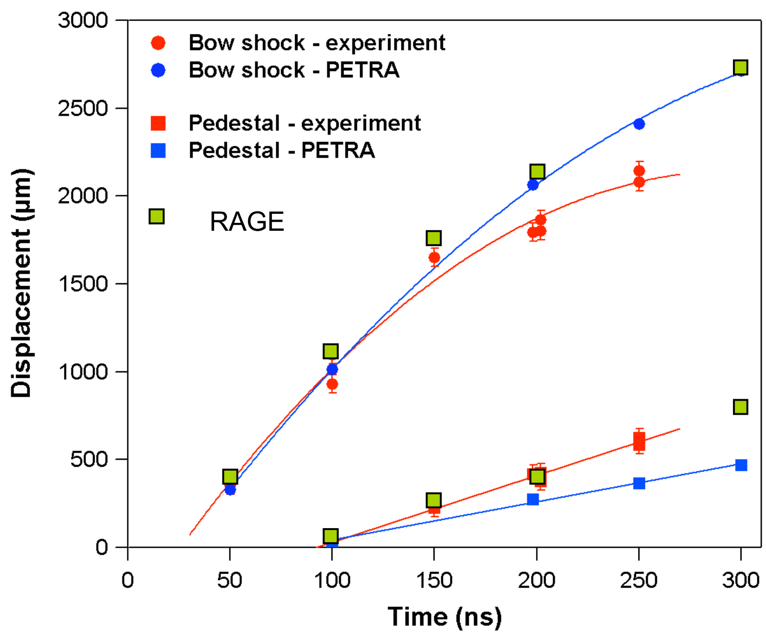
An experiment that shows what the codes can *and* cannot do is the best of all experiments…

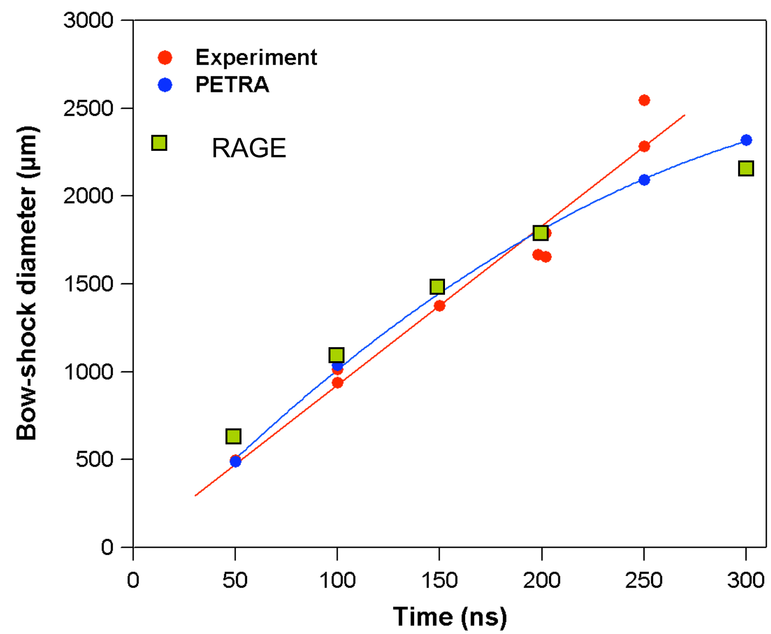
Code Validation

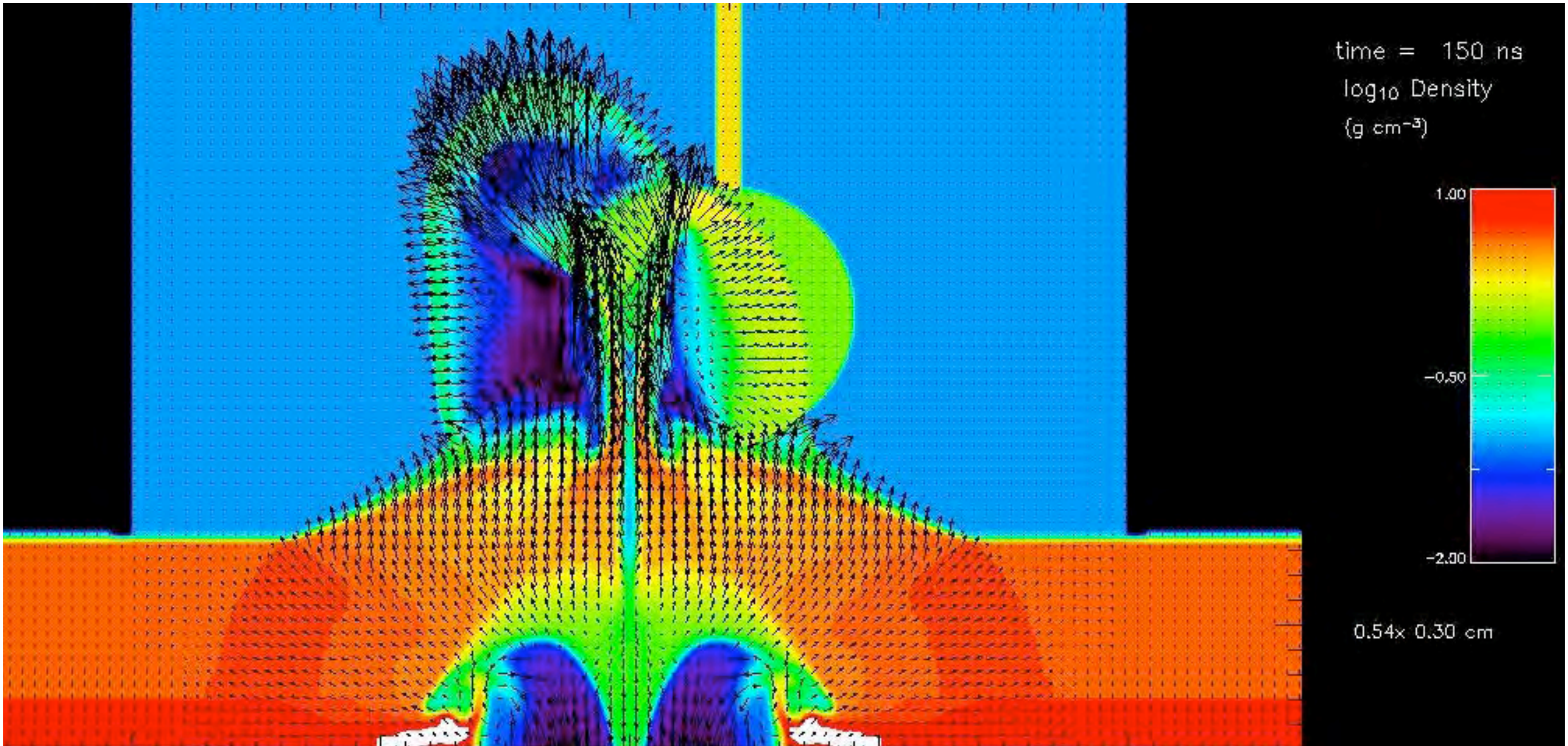
If you can model experiment *A* well, you will have more confidence in modelling astrophysical system *B* (more similar→ more confidence)

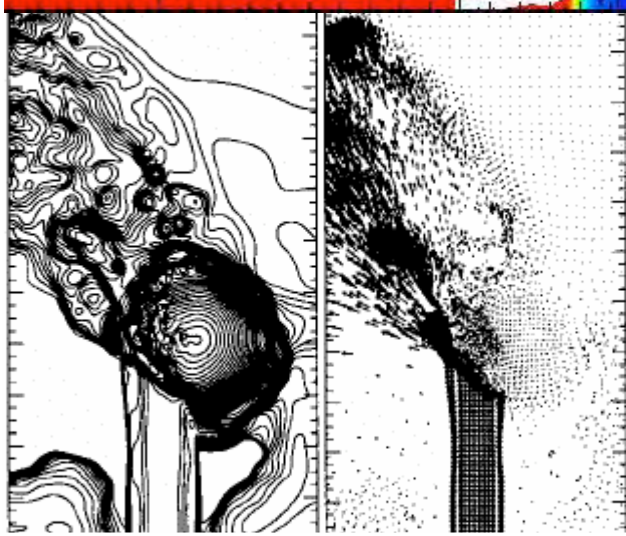


Hohlraum-driven experiment without a ball









Gouveia Dal Pino, ApJ, 526, 862-873 (1999)

RAGE Simulations of experiments
qualitatively resemble
other simulations of HH 110/270

Why Use AstroBEAR?

- AstroBEAR is a 2-D or 3-D AMR code designed specifically for use on astrophysical systems to capture and follow shocks
- AstroBEAR has magnetic fields already available
- Freely available code for use in the astrophysical community

Problems with applying AstroBEAR to Laser Sims

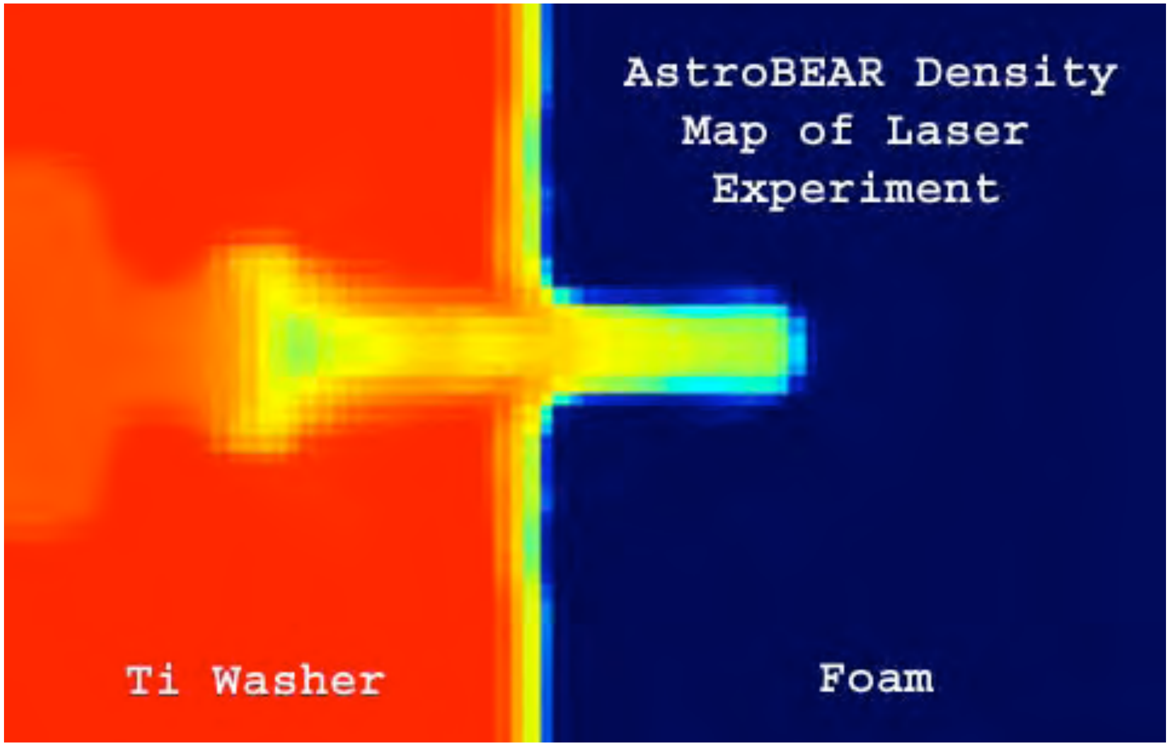
- Does not handle different types of material within the same simulation
- No built-in laser deposition function
- Uses an ideal gas law to calculate the pressure and sound speed, thus creating EOS Issues

Sounds Like a Student Project!

(R. Carver, Rice Ph.D)

Goal:
Enable AstroBEAR to model laser experiments:

- Calculated the pressure and its derivatives using the SESAME tables provided by Los Alamos National Lab.
- Incorporating the ability to track multiple materials within the same simulation
- Calculated the opacities using the SESAME tables to help simulate the actual radiographs obtained during laboratory experiments
- Adding radiation transport capability to better simulate the laser deposition


AstroBEAR Density
Map of Laser
Experiment
Ti Washer
Foam

…But To Compare with Astrophysical Images Need To Model Line Cooling

- Must resolve cooling zones of all shocks
- Must follow highly non-LTE processes of collisional excitation, de-excitation, charge exchange and ionization states of all abundant elements
- Should track ionizing photons

Too Hard.

…Instead…

Another Student Project!

(J. Palmer, Rice University)

Develop a `post-processing' code →

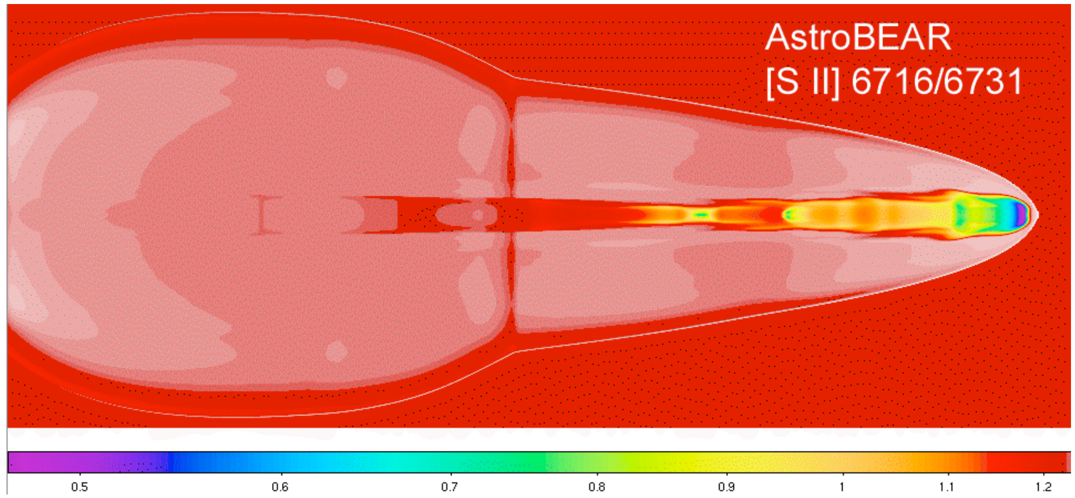
Given: density, temperature, H ionization

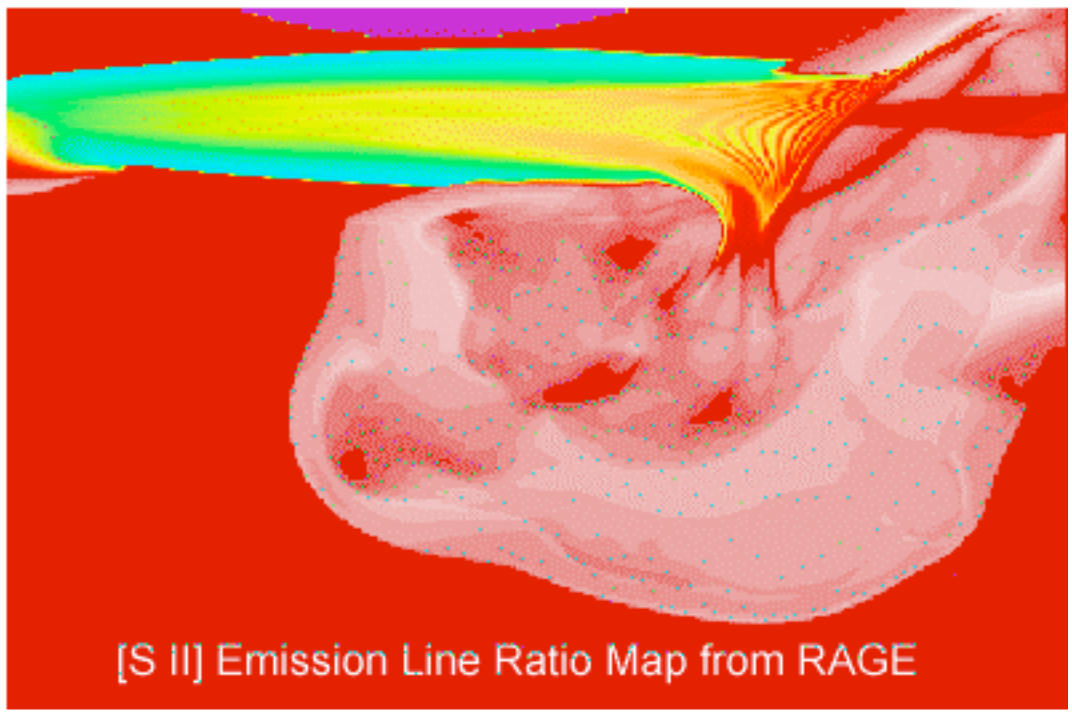
Predict: emission line images of [S II], [N I], [O I] etc

Use charge exchange (very high cross section) to tie H^+/H to N^+/N and to O^+/O. Then given O/H and N/H abundances, densities and temperatures, solve for non-LTE level populations for O I, O II, N I, N II and S II, which then gives radiation rate

Being applied to both RAGE and AstroBEAR

Note: Post-process emission line maps do not affect hydro results (sims include cooling)


AstroBEAR
[S II] 6716/6731
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2


[S II] Emission Line Ratio Map from RAGE

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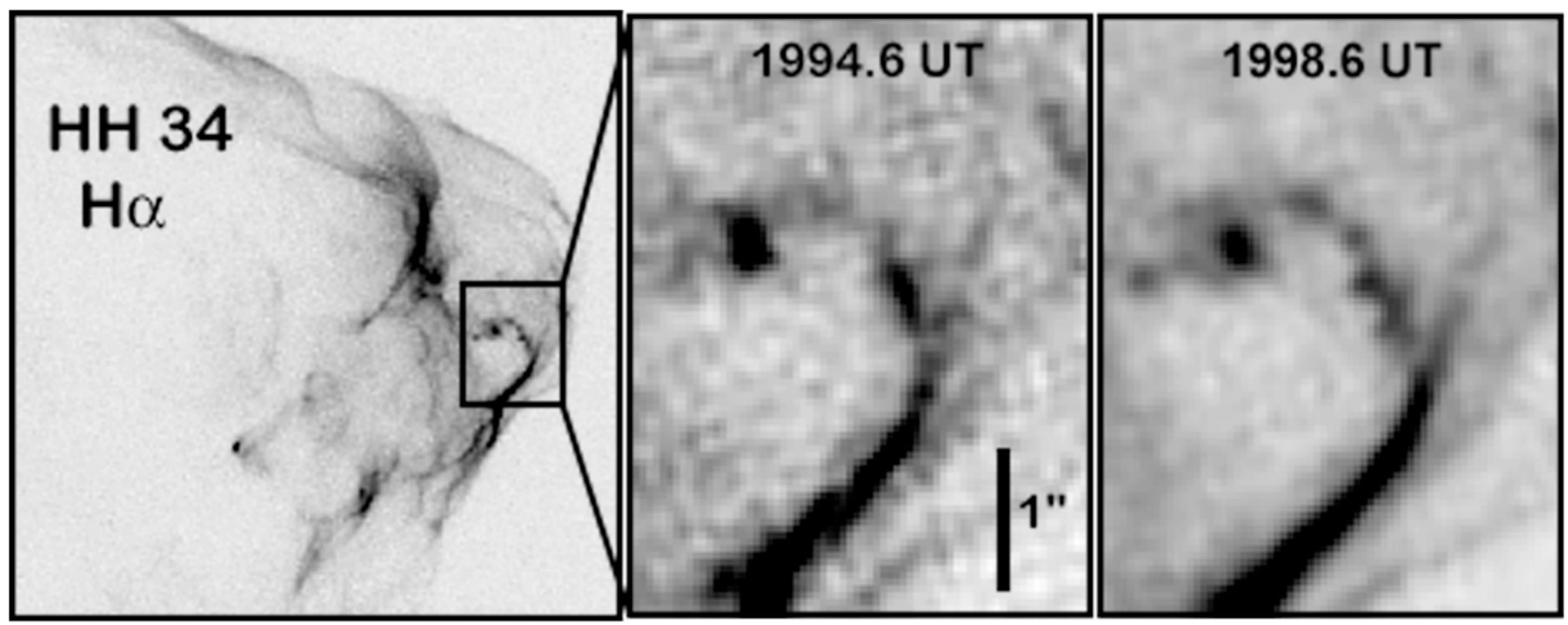
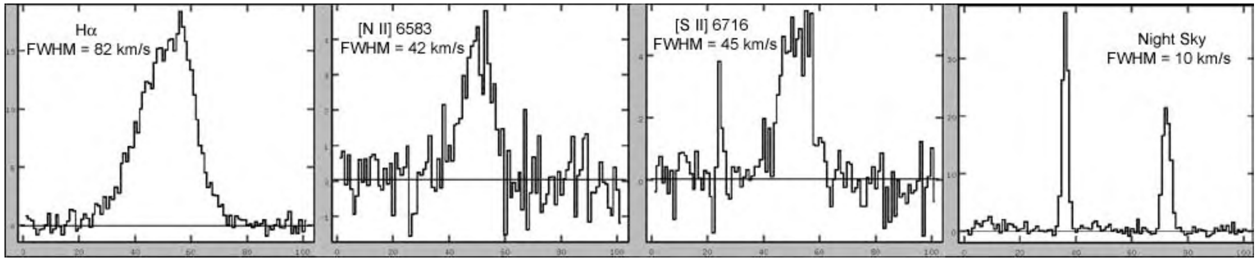


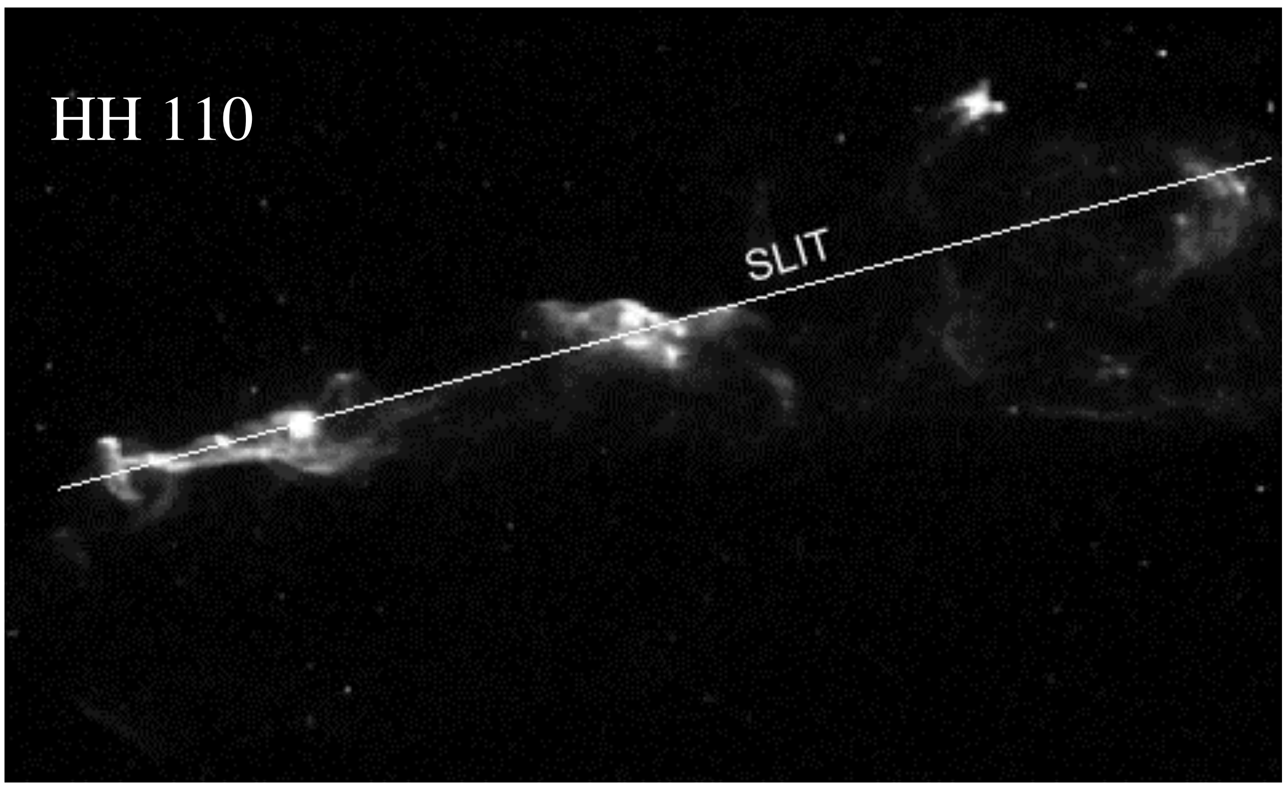
HST project to obtain 3rd epoch to follow instabilities, clumps, and shear

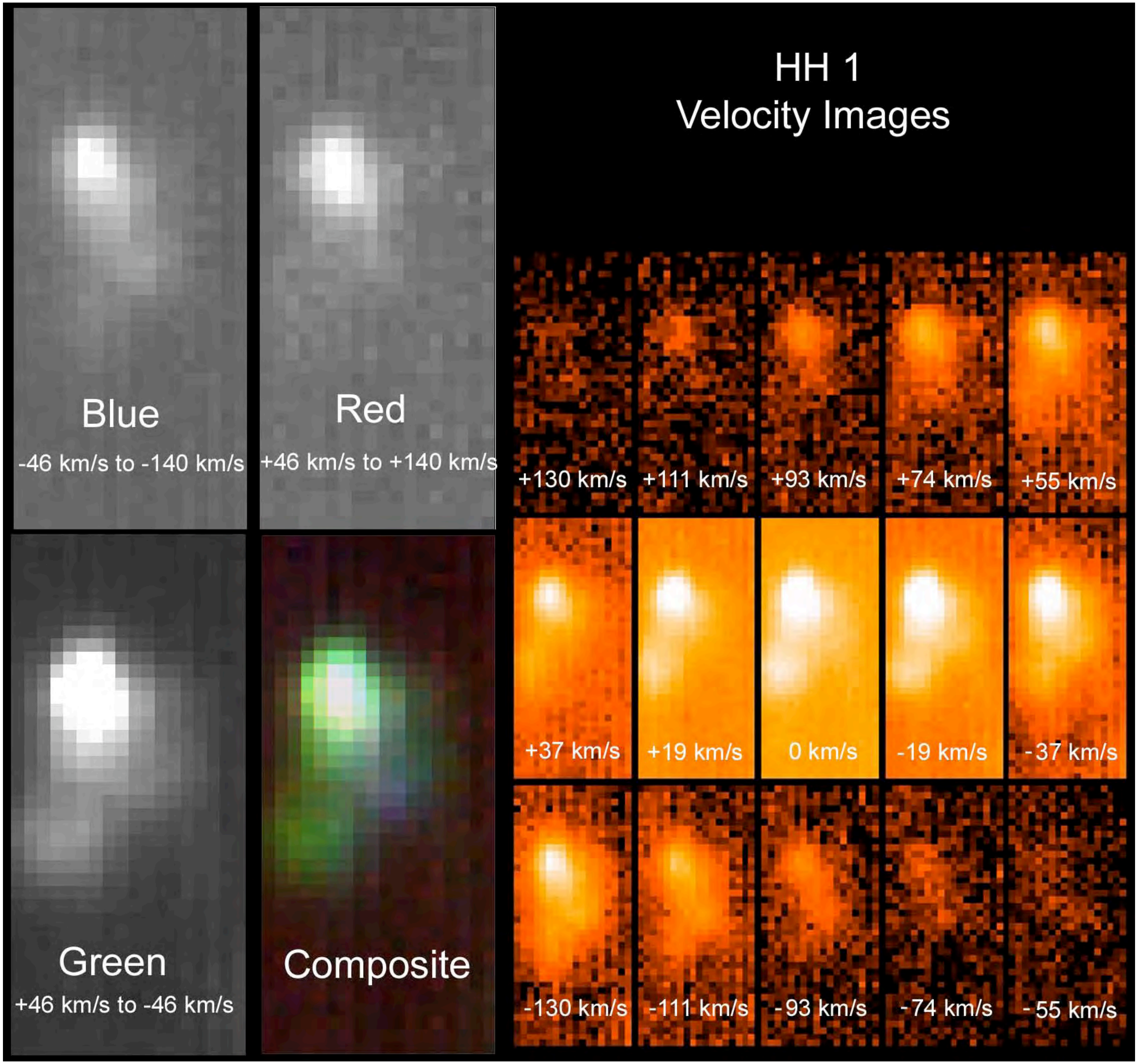
3 targets: HH 1&2, HH 34, HH47

Data to be taken August 2007 – January 2008



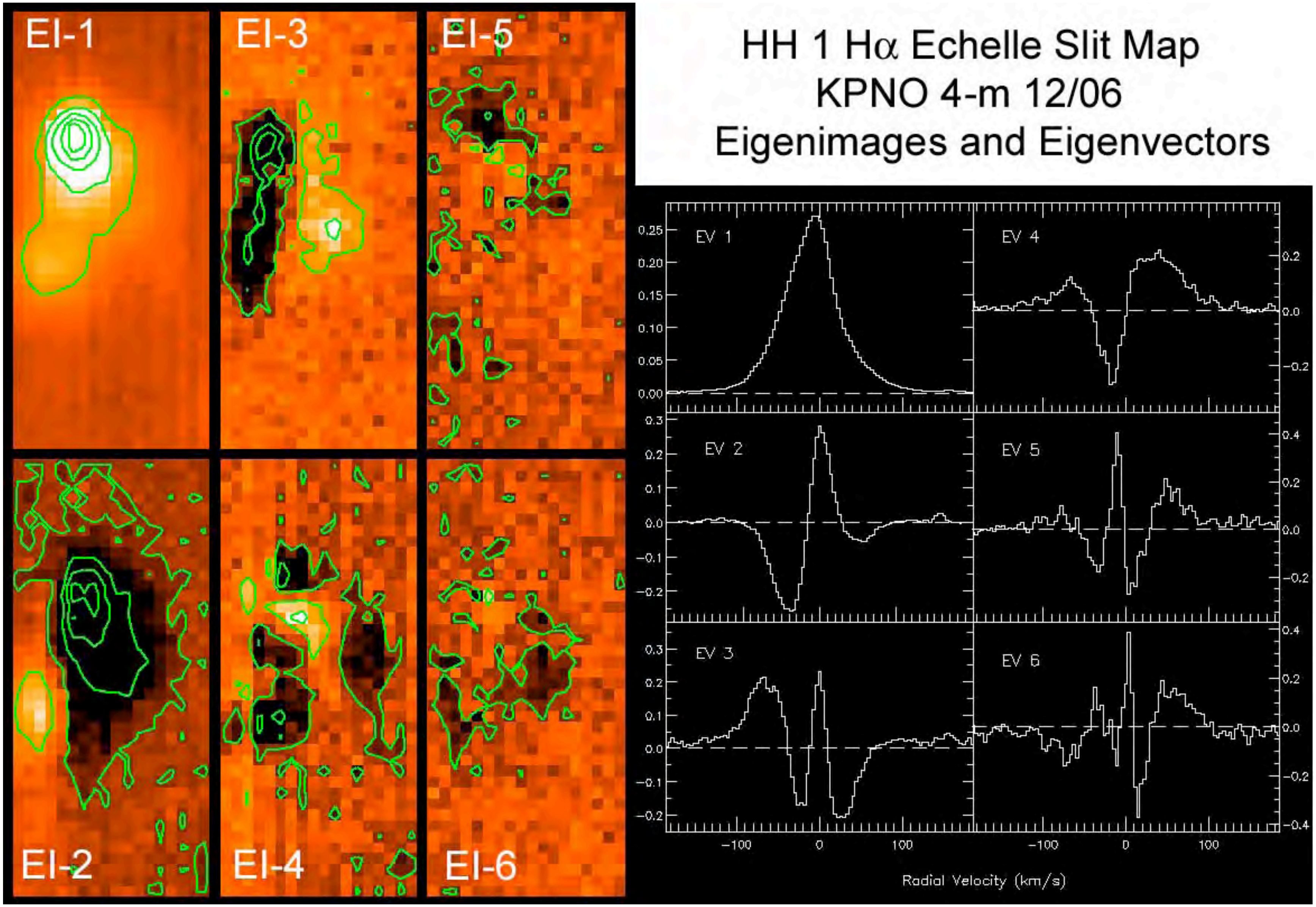
Kitt Peak 4-m spectral mapping to quantify supersonic turbulence in wake of a deflected jet




HH 1
Velocity Images
Blue
-46 km/s to -140 km/s
Red
+46 km/s to +140 km/s
Green
+46 km/s to -46 km/s
Composite
+130 km/s
+111 km/s
+93 km/s
+74 km/s
+55 km/s
+37 km/s
+19 km/s
0 km/s
-19 km/s
-37 km/s
-130 km/s
-111 km/s
-93 km/s
-74 km/s
-55 km/s

Principal Component Analysis

HH 1 Hα Echelle Slit Map
KPNO 4-m 12/06
Eigenimages and Eigenvectors



Summary

- We have a truly multidisciplinary project leading to better understanding of stellar jets by combining:
  - Laboratory Experiments
  - Numerical Simulations
  - Astronomical Observations